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Search for supersymmetry with extremely compressed spectra with the ATLAS and CMS detectors

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Abstract

Results of searches for supersymmetry via direct production of third-generation squarks and gluinos are reported. The analysis use 20.3 fb^{-1} of proton-proton collision data recorded by the ATLAS experiment and 19.5 fb^{-1} recorded by the CMS experiment at a centre-of-mass energy of $\sqrt{s}$=8 TeV. Different signal regions based on monojet-like and c-tagged event selections optimize the sensitivity for direct top squark pair production with small mass differences between the hypothetical supersymmetric particles. In an complementary approach, the heavier top squark is searched for under the assumption that a Z boson is emitted in its decay to the lighter top squark. This strategy retains sensitivity for mass configurations where signals of direct production of the lighter top squark are hard to distinguish from the top quark pair production background. For the case of the gluino, a soft lepton analysis improves sensitivity for small mass differences between the gluino and the lightest neutralino. No significant excess above the Standard Model background expectation is observed in any of the analyses. The resulting limits significantly extend previous results at colliders.

Keywords: Supersymmetry, compressed spectrum, ATLAS, CMS, top squark, gluino

1. Introduction

Supersymmetry (SUSY) is an extension of the standard model (SM) which proposes a super-partner for each SM particle [1, 2, 3, 4, 5, 6] in order to mitigate the virtual contributions of the SM particles to the self energy of the Higgs Boson by contributions with opposite sign [7, 8]. Since the top quark has the largest contribution to the Higgs Boson self energy, the super-partner of the top quark must be light in order to avoid unnaturally large fine-tuning. A similar argument holds for the gluino, because it contributes to the top squark self-energy. Recent searches at the LHC have excluded light top squarks up to 600 GeV [9, 10] and gluinos up to 1.3 TeV [11, 12], however, these results are often obtained under the assumption of a large mass difference to the lightest supersymmetric particle (LSP).

An appealing feature of many R-parity conserving models with SUSY, is that the LSP is stable and a viable dark matter candidate [13, 14]. Many searches therefore require a large imbalance in the total transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$). However, if the mass of the LSP is very close to the parent SUSY particle, almost all of the momentum of the parent SUSY particle is carried by the LSP and the searches with a requirement for large $E_{\mathrm{T}}^{\mathrm{miss}}$ of are not sensitive. Moreover, any decay products of the SUSY particles will fall short of reconstruction thresholds. Such compressed mass configurations have been proposed to reconcile measurements of the dark matter relic density with theoretical predictions of models with SUSY [15, 16] but limits on direct production from collider searches are considerably weaker. At a hadron collider, these models can still be tested by exploting a peculiar property of the strong interaction: The colliding partons of the primary hard interaction can radiate off a high energetic parton that hadronizes and is reconstructed as a jet which recoils against the heavy SUSY system in the transverse plane. This initial-state-radiation jet (ISR-jet) can be

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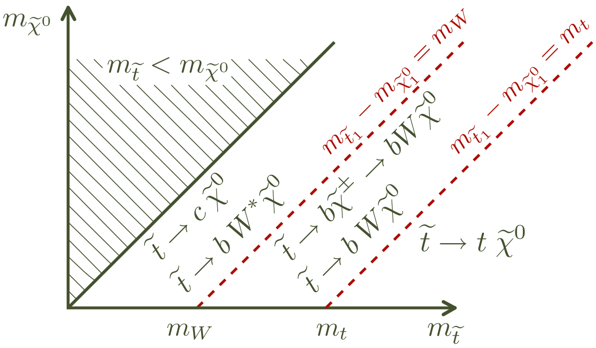


Figure 1: Illustration of the decay modes of the lightest top squark as a function of the top squark mass and the LSP mass.

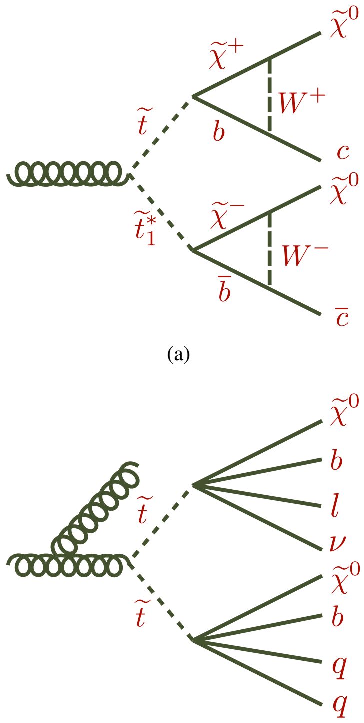


Figure 2: Diagrams for the pair production of top squarks with the decay modes (a) $\tilde{t}_1 \to c + \tilde{\chi}^0_1$ and the four-body decay mode (b) $\tilde{t}_1 \to b, \tilde{\chi}^0_1 + ff$. In one case, the presence of a jet from initial-state radiation is also indicated for illustration purposes.

detected efficienctly and, furthermore, the SUSY decay products receive a boose transverse to the beam direction that facilitates their reconstruction. In this paper, I present a searches for SUSY models with compressed mass spectra in final states with a high energetic ISR-jet and additional soft particles from the decay of the SUSY particles. The results were obtained with the ATLAS detector [17] and the CMS detector [18] using the full 8 TeV dataset (20.3 fb^{-1} for ATLAS and 19.5 fb^{-1} for CMS) and comprise the production of the lightest top squark [19, 20], the second lightest top squark [21, 22] and the gluino [23] with mass configurations that necessitate dedicated reconstruction, selection and analysis techniques. Other searches not mentioned here are the ATLAS top squark searches with soft lepton signal regions [23] and the dilepton top squark search [24]. A complete list of the most current results can be found in Ref. [25] for the CMS experiment and in Ref. [26] for the ATLAS experiment.

2. Searches for the lightest top squark with $m_{\tilde{t}_1} - m_{\tilde{\chi}^0_1} < m_W$

The mass configurations and the most important decay modes of the lightest top squark are summarized in Fig. 1. For a large mass gap satisfying $m_{\tilde{t}_1} - m_{\tilde{\chi}^0_1} > m_t$, the top squark will decay through an on-shell top quark. If $m_W < m_{\tilde{t}_1} - m_{\tilde{\chi}^0_1} < m_t$ the decay will proceed through a on-shell W boson. Below the W boson mass threshold, the four-body decay mode to $(\tilde{\chi}^0_1, b) + ff$ with $ff = l\nu$ or $ff = qq$ is possible. Moreover, there is a competing loop-induced flavour-violating decay mode including a charm quark in the final state [27]. These modes are depicted in Fig. 2 and in the following are considered as separate hypothesis, each with 100% branching ratio. It is furthermore assumed, that the on-shell decay modes involving charged SUSY fermions (charginos) are kinematically forbidden.

The data for the top squark search at the CMS experiment was collected by an online selection (trigger) requiring $E_T^{miss} > 120$ GeV or a high energetic jet and $E_T^{miss} > 105$ GeV [20, 28]. After noise cleaning and removal of beam-related backgrounds, a tight offline requirement of $E_T^{miss} > 250$ GeV and an ISR-jet requirement $p_T(j_1) > 110$ GeV ensures operation in the plateau of the trigger. A second jet is allowed, if it does not exceed a transverse momentum of 60 GeV. In order to remove backgrounds from Z and W production, a veto on isolated leptons (muons or electrons) with $p_T(l) > 10$ GeV is imposed and events with a hadronically decaying tau are vetoed if $p_T(\tau) > 20$ GeV. Signal regions are defined in bins of the transverse momentum of the ISR-jet.The dominating remaining SM backgrounds are Z($\nu\nu$) and W+jets. Data driven background estimation techniques are devised utilizing a μ+jet control sample: The event selection described above is applied, with the exception of the lepton vetoes. From

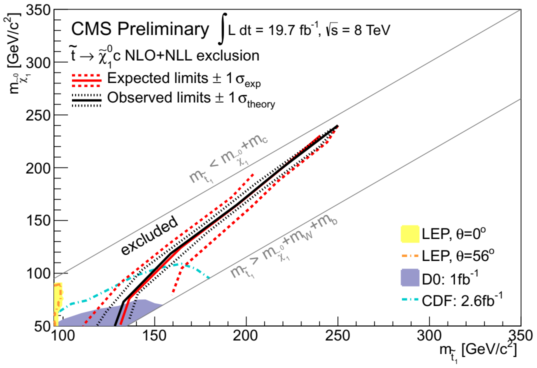
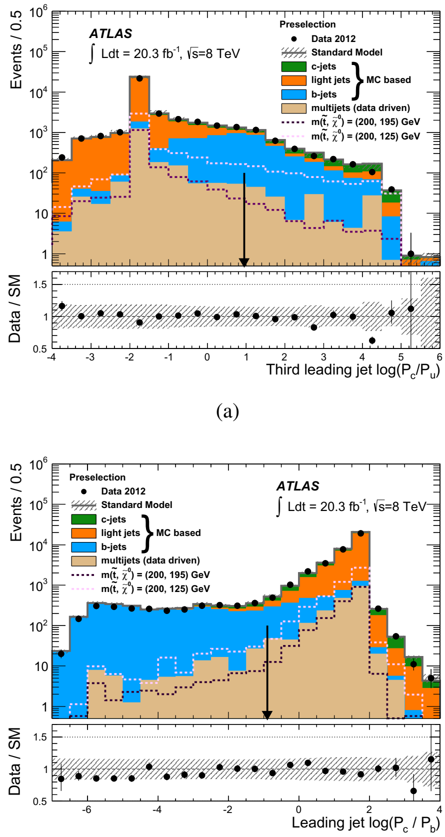


Figure 3: Observed and expected $\pm 1\sigma$ limits on top squark production cross section in the $\tilde{t}_1, \tilde{\chi}_1^0$ mass plane [20].



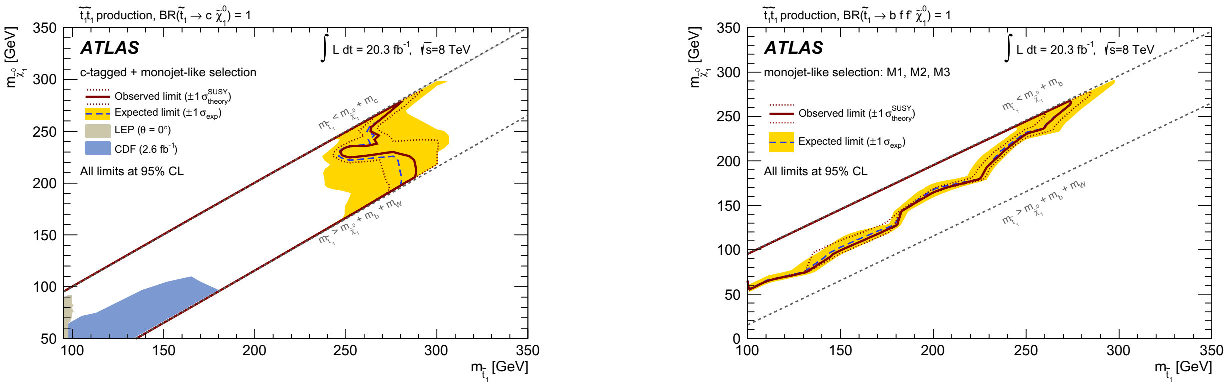
(a)

(b)

Figure 4: Distribution of the discriminator against light jets or gluons $\ln(P_c/P_b)$ for the third-leading jet and against b-jets $\ln(P_c/P_b)$ for the leading jet. Tagging requirements are indicated by arrows. The error bands in the ratios include the statistical and experimental uncertainties in the predictions. For illustration purposes, the distributions of two different SUSY scenarios for stop pair production with the decay mode are included [19].

this sample, Z→ $\mu\mu$ events are used to estimate the Z→ $\nu\nu$ background and W→ $l\nu$ events are used to estimate the remaining W+jets background. The contamination from multijet production (QCD) is estimated by deriving $p_T(j_1)$ dependent scale factors in background dominated control regions and normalizing in the lowest $p_T(j_1)$ bin. Diboson broduction (WW,WZ,ZZ) and top quark production are estimated from simulation with appropriate systematic uncertainties on the production cross sections. After a suitable correction for the muon reconstruction efficiency, the data and the background prediction are compared. No significant discrepancy is observed. The corresponding limit at 95% CL on the top squark production cross section is shown in Fig. 3. Top squarks with masses up to 250 GeV are excluded for sufficiently small mass gaps.

The data for the top squark search [19] with the ATLAS experiment was collected by an $E_\mathrm{T}^\mathrm{miss} > 80$ GeV trigger which is fully efficient at an offline requirement $E_\mathrm{T}^\mathrm{miss} > 150$ GeV. The three monojet-like signal regions are defined by $p_T(j_1) > 280/340/450$ GeV and $E_\mathrm{T}^\mathrm{miss} > 220/340/450$ GeV with similar lepton vetoes as in the CMS analysis. In addition, there are signal regions which require the presence of a reconstructed charm quark. These regions extend the sensitivity to models where $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ approaches m_W in the loop-induced flavour-violating decay mode (Fig. 2a). The c-tagging is performed with a dedicated algorithm using multivariate techniques combining information from the impact parameters of displaced tracks and topological properties of secondary and tertiary decay vertices reconstructed within the jet. The light quark/gluon probability (P_u), the charm jet probability (P_c) and the b-jet probability (P_b) are each provided by the algorithm. They are used to construct the anti-u and anti-b discriminators as $\ln(P_c/P_u)$ and $\ln(P_c/P_b)$, respectively. Their distributions and the working point are shown in Fig. 2 for the third leading jet (anti-u) and the leading jet (anti-b). The kinematic requirements for these regions are $p_T(j_1) > 290$ GeV and either $E_\mathrm{T}^\mathrm{miss} > 250$ GeV or $E_\mathrm{T}^\mathrm{miss} > 350$ GeV. The background estimation for W/Z+jets uses templates obtained from simulation which are corrected for the observed spectra of the vector boson transverse momentum. The top-quark background contribution to the monojet-like analysis is very small and is determined using simulated samples. In the case of the c-tagged analysis, the top-quark background is sizable, as it is enhanced by the jet multiplicity and c-tagging requirements, and is es-



(a) (b)

Figure 5: (a) Observed and expected $\pm 1\sigma$ limits at 95% CL on top squark production cross section in the $\widetilde{t}_1, \widetilde{\chi}^0_1$ mass plane obtained from monojet-like and c-tagged signal regions for the case of the loop-induced decay to a charm quark. (b) Limits on the four-body decay channel obtained from the monojet-like signal regions [19].

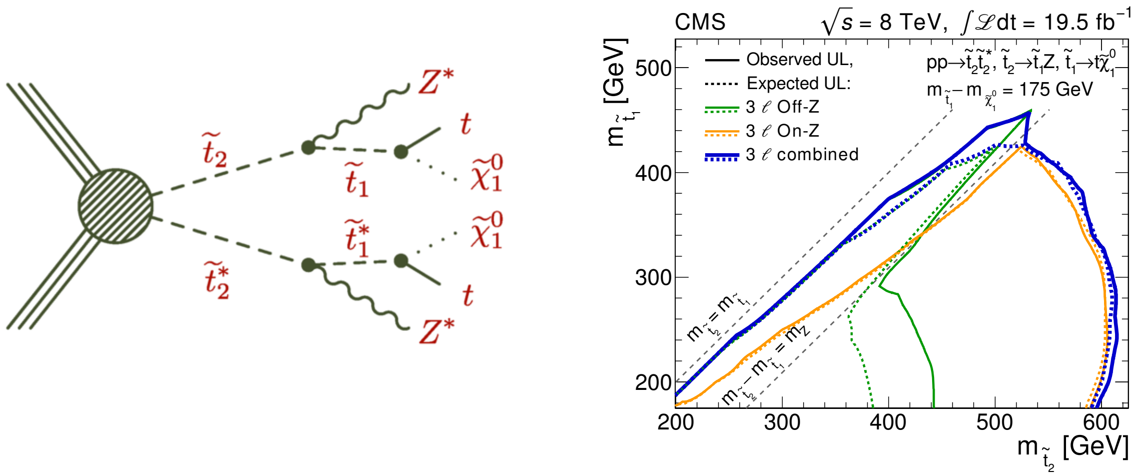
timated using MC simulated samples normalized in a top-quark-enriched control region. The normalization factors are obtained from a simultaneous fit using all control regions and taking into account all statistical and systematical uncertainties as well as correlations. Multijet backgrounds are estimated using a data driven smearing technique. No significant deviation from the SM prediction is observed. The corresponding limits in Fig. 5(a) are strong in particular for larger mass gaps because of the sensitivity provided by the c-tagged signal regions. Top squark masses up to about 240 GeV are excluded at 95% confidence level for arbitrary neutralino masses.Top squark masses up to 270 GeV are excluded for a neutralino mass of 200 GeV. For the scenario with the four-body decay where the top squark and the lightest neutralino are nearly degenerate in mass, top squark masses up to 260 GeV are excluded.

3. A search for the next to lightest top squark

If $m_{\widetilde{t}_1} - m_{\widetilde{\chi}^0_1} \approx m_t$ the kinematic of top squark pair production is very similar to top quark production and inclusive searches for $\widetilde{t}_1$ are insensitive. In this case, it is interesting to search for the heavier top squark in the $\widetilde{t}_2 \to Z^* + \widetilde{t}_1$ decay channel as shown in Fig. 6(a) and as described in more detail in [21, 22]. Here, the CMS result [21] is reported because it comprises configurations with top squark mass gaps below the Z boson mass. The online selection requires two isolated leptons (muons or electrons) which is fully efficient after an offline requirement of at least three leptons with $p_T > 10$ GeV and one of them with $p_T > 20$ GeV. Furthermore, two jets are required and one of them must be b-tagged satisfying the medium working point of the tagger. Events are furthermore classified into "on-Z" and "off-Z" depending on whether or not a same flavour pair of leptons with opposite charge is found with an invariant mass within 15 GeV of the nominal Z boson mass. The "off-Z" region provide sensitivity for models with $m_{\widetilde{t}_2} - m_{\widetilde{t}_1} < m_Z$. The background estimation of the fake lepton contribution uses a data-driven technique based on a measurement the lepton fake rate in a signal-free control region and uses a sideband with loosely isolated leptons to estimate the number of events with at least one fake lepton in the signal region. Smaller electroweak backgrounds are estimated from simulation and the procedure is validated in control regions. The final background prediction agrees with the observation for both the off-Z and the on-Z signal regions. The corresponding limits shown in Fig. 6(b) nicely illustrate how the two classes of signal regions combine to give a tight limit for a large portion of the parameter space. The heavier top squark is excluded below approximately 575 GeV for $m_{\widetilde{t}_1}$ below approximately 400 GeV.

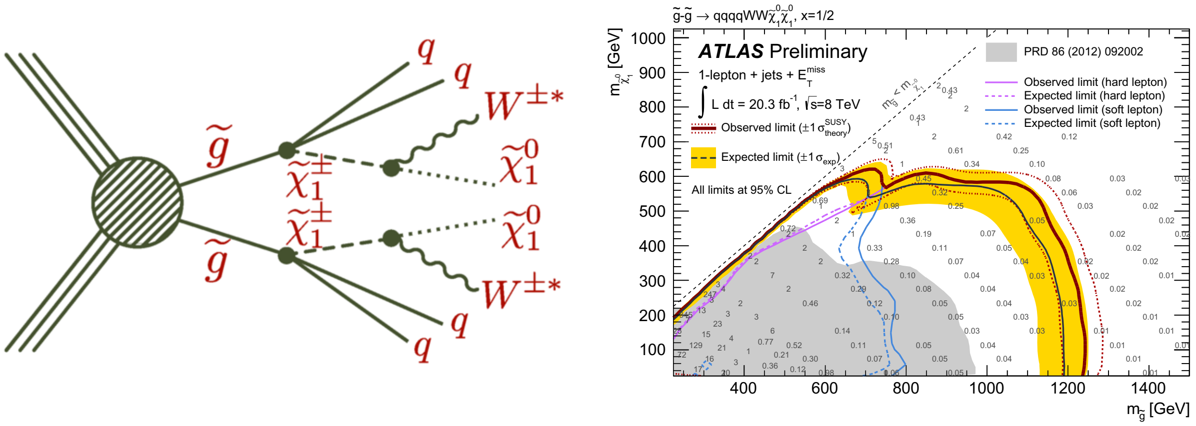
4. A search for gluinos

A search for gluinos decaying through the lightest chargino into a final state with first or second generation quarks is presented in Ref. [23]. The chargino is assumed to satisfy $m_{\widetilde{\chi}^\pm_1} = 1/2(m_{\widetilde{g}} + m_{\widetilde{\chi}^0_1})$ and final states with a large degree of compression of the gluino and the neutralino are considered, see Fig. 7(a). For the online event selection, muon+jet+$E_{\mathrm{T}}^{\mathrm{miss}}$ and



(a) (b)

Figure 6: (a) Illustration of the decay modes of the $\widetilde{t_2}$ to the lightest top squark and a Z boson. (b) Exclusion limits for the production of the heavier top squark assuming the relation $m_{\widetilde{t_1}} - m_{\widetilde{\chi}_1^0} \approx m_t$ as a function of $m_{\widetilde{t_1}}$ and $m_{\widetilde{t_2}}$. As indicated in the legends, the thinner curves show the results from each of the contributing channels, while the thicker curve shows their combination [21].



(a) (b)

Figure 7: (a) Illustration of the decay modes of the gluino to the lightest chargino and a subsequent decay to the lightest neutralino which is assumed to be the LSP. (b) Exclusion limits for gluino production [23] as a function of $m_{\widetilde{g}}$ and $m_{\widetilde{\chi}_1^0}$.

electron+$E_{\mathrm{T}}^{\mathrm{miss}}$ triggers are used with threshold $p_T(l) >$ 24 GeV. These hard lepton regions are supplemented by soft lepton signal regions that are selected by a trigger requiring $E_{\mathrm{T}}^{\mathrm{miss}} > 80$ GeV that is fully efficient after an offline requirement of $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV and $p_T(j_1) >$ 60 GeV. The soft signal regions require a muon with $6 < p_T < 25$ or an electron with $10 < p_T < 25$ GeV and have no overlap with the hard lepton signal regions which require $p_T(l) > 25$ GeV. Additional tight requirements for all regions on $E_{\mathrm{T}}^{\mathrm{miss}}$, the jet multiplicity and the transverse mass of the lepton-$E_{\mathrm{T}}^{\mathrm{miss}}$ system provide high sensitivity for signals with large mass gaps and the soft lepton regions retain sensitivity for the compressed spectra. The background estimation for electroweak boson production and top quark pair production employs a simultaneous fit that uses translation factors from control to signal regions (obtained from simulation), observations in signal-free control regions and simulated yields for the smaller single-top, diboson and $t\bar{t}$+W/Z backgrounds. The final background estimation agrees with the observation and the corresponding limits are shown in Fig. 7(b). The soft lepton signal regions help put tight limits on models with compressed spectra such that gluinos with masses below 1.2 TeV are excluded for LSP masses below 550 GeV.

5. Summary

Results on searches for signals of supersymmetry with compressed spectra were obtained using the full 8 TeV dataset of the ATLAS and the CMS experiment. Observations in regions sensitive to signals from decays of the lightest top squark, the second lightest top squark and the gluino were all found to be in agreement with the SM. Sophisticated reconstruction techniques comprising the online selection using the $E_{\mathrm{T}}^{\mathrm{miss}}$ observable, low-p_T lepton reconstruction and c-tagging provided sensitivity even for extremly compressed spectra. The new limits obtained in this way, significantly extend previous results.

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